

## HEAVY VEHICLE PROPULSION MATERIALS

Advanced materials are an enabling technology for fuel-efficient heavy-vehicle truck engines. The Heavy Vehicle Propulsion Materials Project is organized around the following technology issues: fuel systems; exhaust aftertreatment; air handling, hot section and structural components; and standards.

### Materials for Fuel Systems

The fuel systems for diesel engines are complex, expensive systems that are critically important to meeting the efficiency and emissions targets of the Office of FreedomCAR and Vehicle Technologies (OFCVT). Virtually every path to improving the control of the combustion process in order to improve efficiency and reduce emissions depends on improvements in the fuel injection system.

Fuel injectors are highly precise systems. The individual components must fit together with clearances that are sometimes smaller than  $1 \times 10^{-6}$  meters. Control of the combustion process requires precise control of the size, shape, and surface finish of the injector components. The current systems for reliably controlling multiple injections are limited by the ability of mechanical and electronic systems to respond precisely and quickly enough to provide the additional control of injection. Smart materials, such as piezoelectric materials, offer the potential for better control of fuel injection and have recently been introduced for automobiles. However, a number of improvements in materials and manufacturing methods for the materials are yet required for heavy vehicles.

Presently, the fuel system represents a significant portion of the cost of a heavy-duty diesel engine. Enabling materials and cost-effective precision manufacturing processes are instrumental in developing improved fuel injection systems. In addition to new and improved materials, improved manufacturing and inspection methods for the injector components are being developed.

Two important research and development (R&D) efforts were completed in FY 2003. A coordinated project was completed for developing the materials and manufacturing technology for a new generation of wear- and scuff-resistant fuel system components. The participants included Cummins Engine Company, CoorsTEC, Oak Ridge National Laboratory (ORNL), Southern Illinois University at Carbondale, and the University of Colorado. The material developed is a cermet made of a nickel aluminide matrix and a titanium carbide (TiC) ceramic phase. The material is very wear- and scuff-resistant and can be engineered to match the coefficient of thermal expansion of steel. Cummins, the user of the material, provided all the design and materials requirements and performed the prototype testing. CoorsTEC, a ceramic manufacturer that presently supplies zirconia ceramic components to Cummins, is developing the cermet manufacturing technology. ORNL invented the nickel aluminide-TiC cermet and performed much of the cermet processing and microstructure development. The University of Colorado developed processes for synthesis of cost-effective powders for manufacture of the material. Southern Illinois University at Carbondale developed two low-cost manufacturing processes for the cermet material: low-pressure injection molding and continuous sintering in a belt furnace.

The feasibility of piezoelectric actuators for heavy-duty diesel engine fuel injectors was demonstrated in a recently-completed project. Detroit Diesel Corporation (DDC), completed a project that had the objective of developing technical requirements for a valve actuator system, including advanced piezoelectric materials that would enable faster and more precise

control of the injection rate characteristics of a heavy-duty diesel injector. ORNL and Wayne State University provided materials development and testing for the project. DDC's research resulted in the following conclusions:

1. A piezoelectric (piezo) stack is a viable actuation device for future diesel fuel injection equipment involving multiple actuators.
2. Piezo actuation provides substantially faster mechanical and hydraulic response times than prevailing commercial solenoid actuator technology.
3. Hydraulic amplification of piezo stack displacement can generate required diesel injector control valve motion.
4. Hysteresis of a piezoelectric stack is not expected to play a significant role in a pulsed application such as a fuel injection system.
5. Open-loop control of input voltage may be of adequate complexity for a mature piezo actuator application in a diesel fuel injection system.
6. Commercially available piezo stacks have adequate material properties and technical characteristics for fuel injection.

## Materials for Exhaust Aftertreatment

The reduction of nitrogen oxide ( $\text{NO}_x$ ) and particulate emissions is critically important to OFCVT's program and is highly materials-dependent. The U.S. Department of Energy's goals for improved efficiency of heavy vehicles are greatly complicated by engine design and exhaust aftertreatment technologies designed to meet the mandatory U.S. Environmental Protection Agency (EPA) emission regulations for 2007 and 2010. Materials and systems research is being conducted to minimize the potentially negative effects of emission-reduction technologies on fuel economy and to result in both cleaner and more efficient engines.

The durability of exhaust aftertreatment systems in heavy vehicles is a concern. Lifetimes of at least 500,000 miles are expected, and a million-mile lifetime is desired (compared with 100,000 miles for automobiles). Exposure of the aftertreatment systems to high temperatures, vibration, erosion, and chemical attack by species in the oil and fuel results in degradation of performance. In an effort to develop more durable systems, the effects of exposure during service on the microstructure and microchemistry of the aftertreatment systems are being characterized. The development of advanced  $\text{NO}_x$  sensors is being conducted to facilitate optimal engine and aftertreatment control strategies.

Accomplishments in FY 2003 include significant progress in a collaborative Ford Motor Company-ORNL program that seeks to facilitate deployment of a  $\text{NO}_x$  trap for lean diesel or gasoline exhaust. The effort includes (1) investigating materials issues related to deterioration of  $\text{NO}_x$  trap performance after aging as a result of thermal and sulfation-desulfation cycles and (2) investigating materials that are robust under the lean  $\text{NO}_x$  trap operating conditions. The second objective includes the synthesis of new materials.

Research conducted at the High Temperature Materials Laboratory at ORNL is focused on the development and use of new capabilities and techniques for ultra-high-resolution transmission electron microscopy to characterize the microstructures of catalytic materials of interest for reduction of  $\text{NO}_x$  emissions in diesel and automotive exhaust systems. This research aims to demonstrate the effects of reaction conditions on changes in morphology of heavy metal species on "real" catalyst support materials, typically oxides.

Exhaust aftertreatment materials projects are ongoing at both Caterpillar, Inc., and Cummins. These projects are significant in that they represent a departure from an earlier culture in which the diesel engine companies relied heavily on catalyst manufacturers to

provide the needed technologies and did not actively participate in the development of catalyst materials. These diesel engine manufacturers are actively collaborating with catalyst suppliers in the development of improved catalyst materials and are contributing to the development of a fundamental understanding of catalyst performance that is important to both suppliers and users of catalyst systems.

Ford and ORNL are collaborating on the development of a NO<sub>x</sub> sensor that can be used in systems for on-board remediation of diesel engine exhaust. The sensor should have an operating temperature of 600–700°C and be able to measure NO<sub>x</sub> concentrations from 0 to 1500 ppm at oxygen levels from 5 to 20 vol %. Prototype sensing elements are fabricated by patterning electronically conductive and catalytic layers onto oxygen-ion-conducting substrates. The sensing elements are characterized for NO<sub>x</sub> response, oxygen sensitivity, and response time. These results, along with microstructural characterization, should point to the correct combination of materials chemistry, materials processing, and sensor design required for the desired sensor performance.

## **Materials for Air Handling, Hot Section, and Structural Applications**

Engine design strategies for meeting EPA emission requirements have resulted in the need for significantly higher turbocharger boost. The higher boost requirements result in higher heat of compression and greater thermal and fatigue loads on turbocharger components.

Caterpillar began a new project in 2003 to design and fabricate a cost-competitive diesel engine turbocharger, using lightweight titanium materials, that provides a reduction in both fuel consumption and transient emissions. Caterpillar has designed a series turbocharger for use on the C15 engine platform. It consists of one turbo wheel and two compressor wheels that are attached to a single rotating drive shaft. This compact design will replace a two-turbocharger system presently installed in the C15 engine. Titanium aluminide will be used for the turbo wheel, and one of the compressor wheels will be made from a titanium alloy.

In a related project, Dynamet Technologies, Inc. is conducting an R&D project to develop low-cost Ti-6Al-4V billet feedstock using a blend of titanium and alloy powders and inexpensive Ti-6Al-4V machine turnings. Dynamet will evaluate this low-cost titanium alloy feedstock as starting billet material for casting, forging, and extrusion operations.

Caterpillar and ORNL won a 2003 R&D 100 Award for the development of CF8C-Plus cast stainless steel. The new high-temperature stainless steel may have near-term applications in diesel engine exhaust manifolds and turbocharger housings. The future direction for this project includes completing the evaluation of thermal fatigue properties and aging resistance after 10,000 hours, characterizing microstructural changes after selected high-temperature testing or aging, and evaluating the effects of different commercial-scale casting processes on properties of CF8C-Plus steel.

Caterpillar, in a collaboration with Argonne National Laboratory and ORNL, has a project to design and fabricate prototype engine valves from silicon nitride and titanium aluminide materials that are 30% lighter than steel valves, provide a 200% increase in service lifetime, and may increase fuel efficiency by 10% in a camless engine design. Caterpillar is also developing innovative approaches to thermal barrier coatings and wear-resistant coatings for engines. The durability of thermal sprayed coatings, particularly thermal barrier coatings,

remains the major technical challenge to their implementation in new engine designs. New approaches to coating design and fabrication are being developed to aid in overcoming this technical hurdle. Specific objectives are

- Laser technologies of surface dimpling, cleaning, and laser-assisted spraying to enhance adherence and increase coating strength.
- Development of phosphate-bonded composites for thermal management coatings.
- Evaluation of quasicrystalline materials as potential thermal barrier and wear coatings.

## Materials and Testing Standards

OFCVT has an International Energy Agency (IEA) "Implementing Agreement for a Programme of Research and Development on Advanced Materials for Transportation Applications" (IA-AMT). The objectives of the IA-AMT are (1) to identify and evaluate promising new processing and surface engineering technologies capable of improving materials performance in transportation systems and (2) to promote and implement pre-competitive development and verification of advanced characterization methods appropriate for advanced materials for transportation applications. Annex III, which was approved in July 2002, consists of two subtasks on contact reliability of advanced engine materials, including structural ceramics, composites, and nanostructured friction/wear coatings. Subtask 1 is an information exchange; Subtask 2 focuses on the development of standard test methods and procedures for determining the rolling contact fatigue resistance of advanced materials. The European Community plans to invite the United Kingdom to join the IA-AMT because of its interest in participating in Annex III. Preliminary discussions have been held with government officials from Canada concerning the initiation of a new Annex on lightweighting of materials.

A new activity to be conducted under the IEA program is being developed by the National Institute of Standards and Technology (NIST). The objectives of this new effort are as follows:

- Organize an international cooperative research program on an integrated surface modification technology under the auspices of the IEA.
- Design and identify surface features and patterns that can achieve friction reduction and enhanced durability for heavy-duty diesel engine components.
- Develop the understanding and appropriate models to explain texturing effects on frictional characteristics.
- Develop appropriate thin films and coatings to achieve synergistic and complementary relationships with texturing to enhance performance.
- Discover and develop the surface chemistry for protecting the films and coatings that work in synergy with the textures.

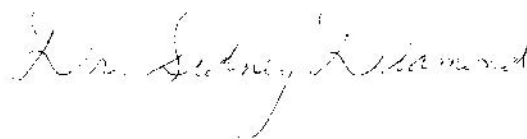
NIST also leads a project to develop standard testing methods for advanced materials, primarily ceramics. Step by step, we are building a national and international standards infrastructure to facilitate the commercial utilization of new advanced materials in engine applications. The generic test method standards developed to date have proved to be so practical, reliable, and versatile that they are now being used to support a wide range of applications, including surgical implants in humans and even ceramic military body armor.

Test methods relevant to ceramic materials and heavy-vehicle propulsion applications are investigated, refined, and standardized. Round-robins are conducted as necessary. Standard Reference Materials (SRMs) are created to support the test methods and materials

specifications. Procedures are standardized by the American Society for Testing and Materials (ASTM) and/or the International Organization for Standards (ISO). In FY 2003, SRM 2831 for Vickers Hardness of Ceramics and Hard Metals was finished. This SRM complements ASTM and ISO test methods standards for Vickers hardness of hard materials, and new material specification standards such as ASTM F 2094 for silicon nitride for ball bearings.



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